What Will Improvements in Astrometry do for…

GALACTIC DYNAMICS?

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Key point: measurements of a few micro-arcsecond accuracy will afford us the first **full phase-space (!)** sampling of the stellar distribution in the Galaxy.
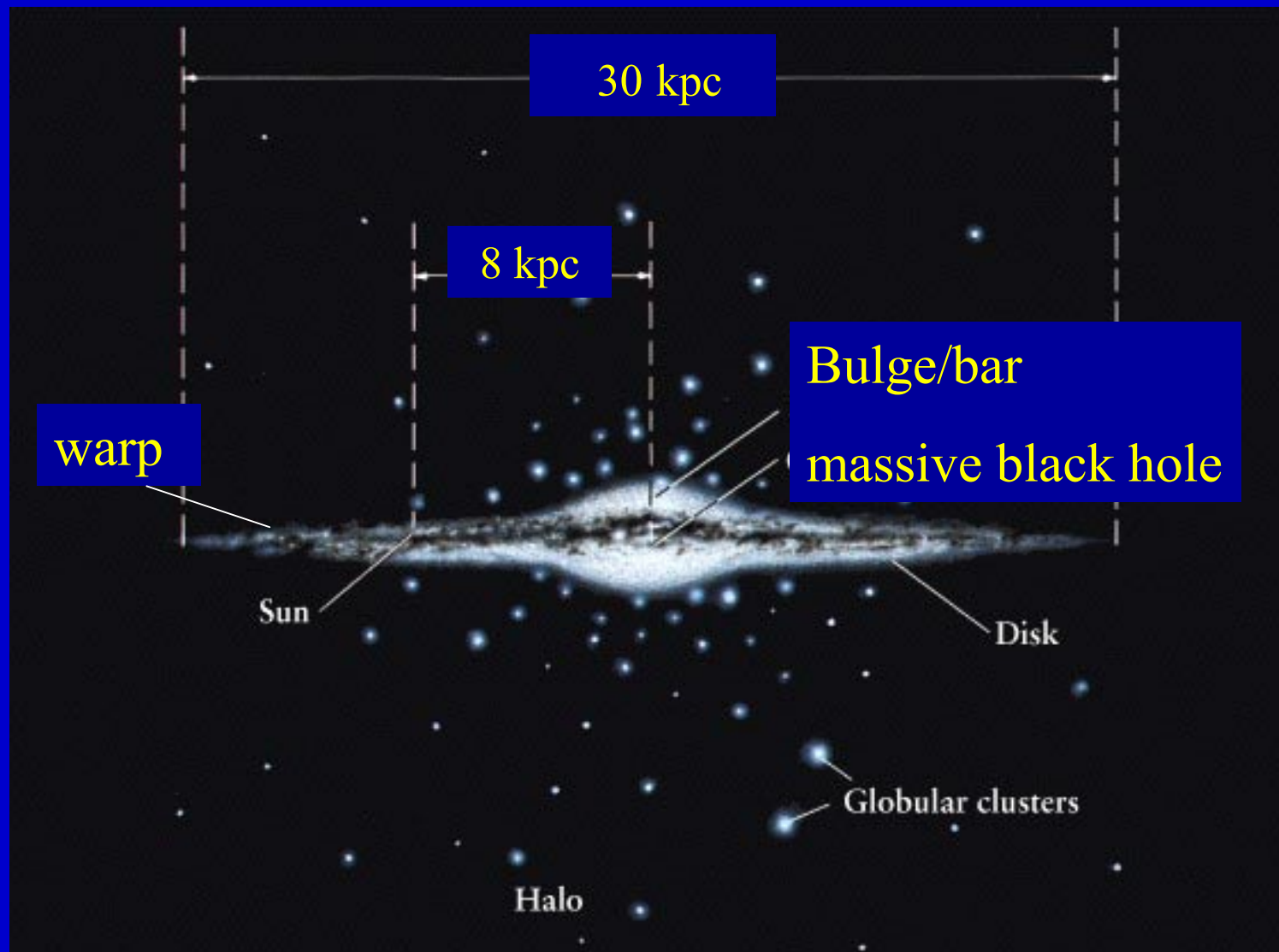
Outline

0. Introduction: Galactic scales and astrometric accuracy.

1. The Galactic reference frame and rotation curve.

2. The dark matter halo

3. Constraints on galaxy formation

4. Summary

Note: [reference list] at end.

0. Introduction

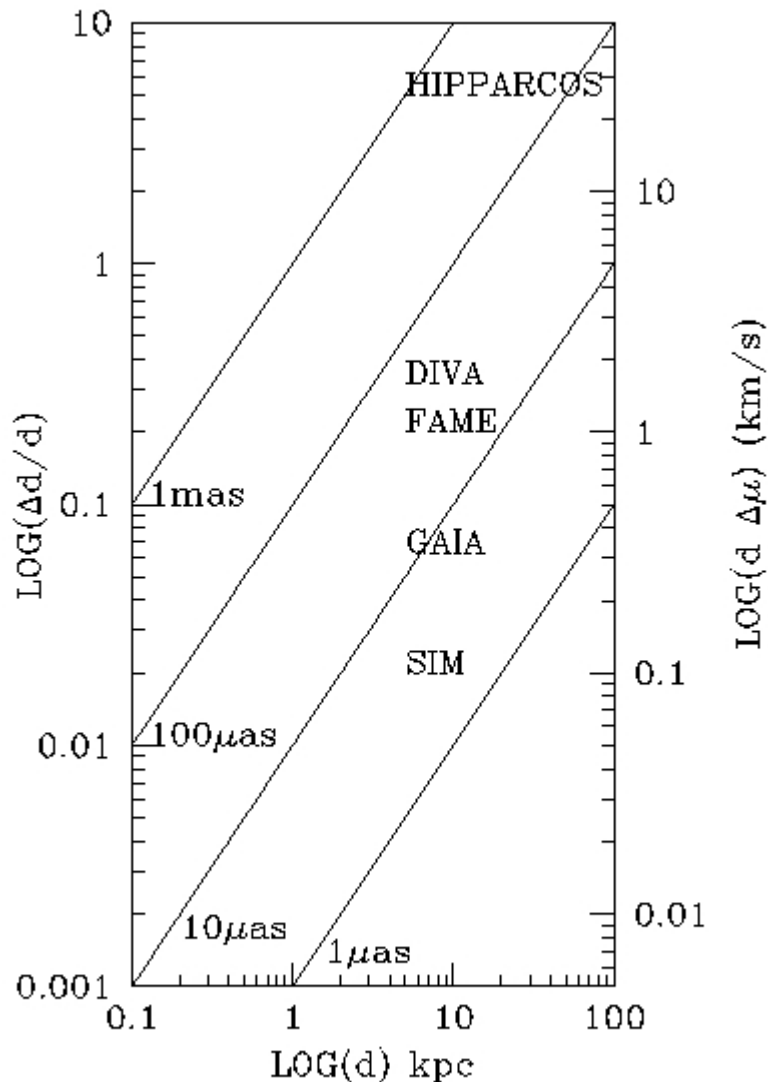## What DO we know about the Galaxy?

What DON'T we know about our Galaxy?

- Distance from Sun to Galactic center:7.5 - 8.5 kpc? [1,2]

- Motion of Sun about Galactic center:180-220 km/s? [3-5]

- Rotation curve outside Solar Circle: flat/falling/rising? [5]

- Mass enclosed within 50kpc: unknown to +100/-50% [6]

- Distribution of halo stars? [7-9]

   Other problems we'd like to know more about: dark matter in the disk; Galactic bar; warp; spiral arms; dark matter content of satellite galaxies…...

Astrometric accuracy on Galactic scales

$$\frac{\Delta d}{d} \approx 0.1 \times$$

$$\left(\frac{d}{10\,\text{kpc}}\right) \times \left(\frac{\Delta p}{10\mu\text{as}}\right)$$

$$\Delta v = d\Delta\mu \approx 0.5\,\text{km/s} \times$$

$$\left(\frac{d}{10\,\text{kpc}}\right) \times \left(\frac{\Delta\mu}{10\mu\text{as/yr}}\right)$$

d = distance

v = tangential velocity

Δp = parallax error

$\Delta\mu$ = proper motion error

The revolution in astrometric accuracies (and magnitude limit!) will allow us to look on truly Galactic scales:

Hipparos 10% horizon

(Note: the "best" standard candles have 10% uncertainties)

The SIM 10% horizon

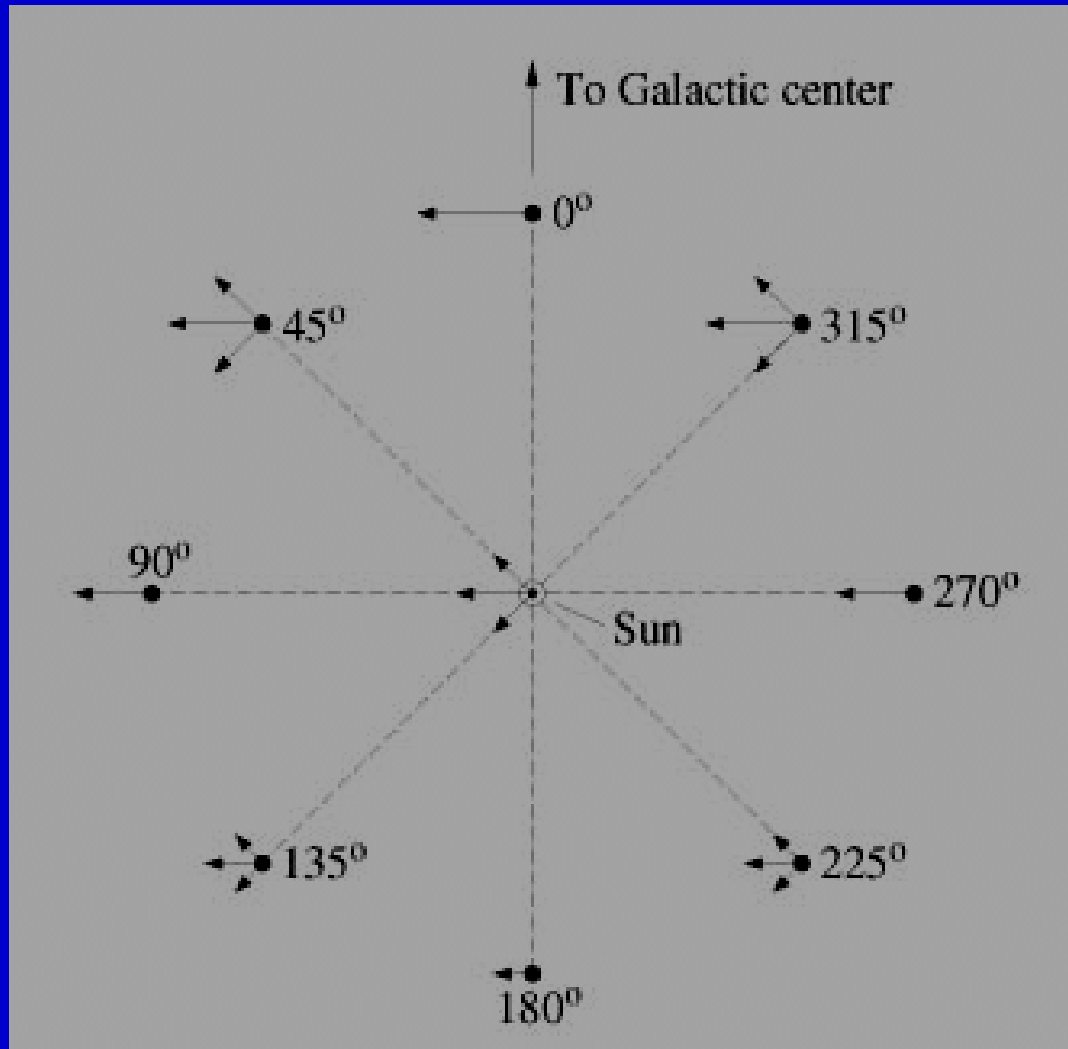# 1. The Galactic reference frame and rotation curve

To build a complete Galactic model need to know, relative to the Galactic center:

$R_0 = $ distance of Sun

$\Theta_0 = $ circular speed at R_0

$\Omega_0 = \Theta_0 / R_0$

Current problem: need to understand everything relative to our rotating reference frame.
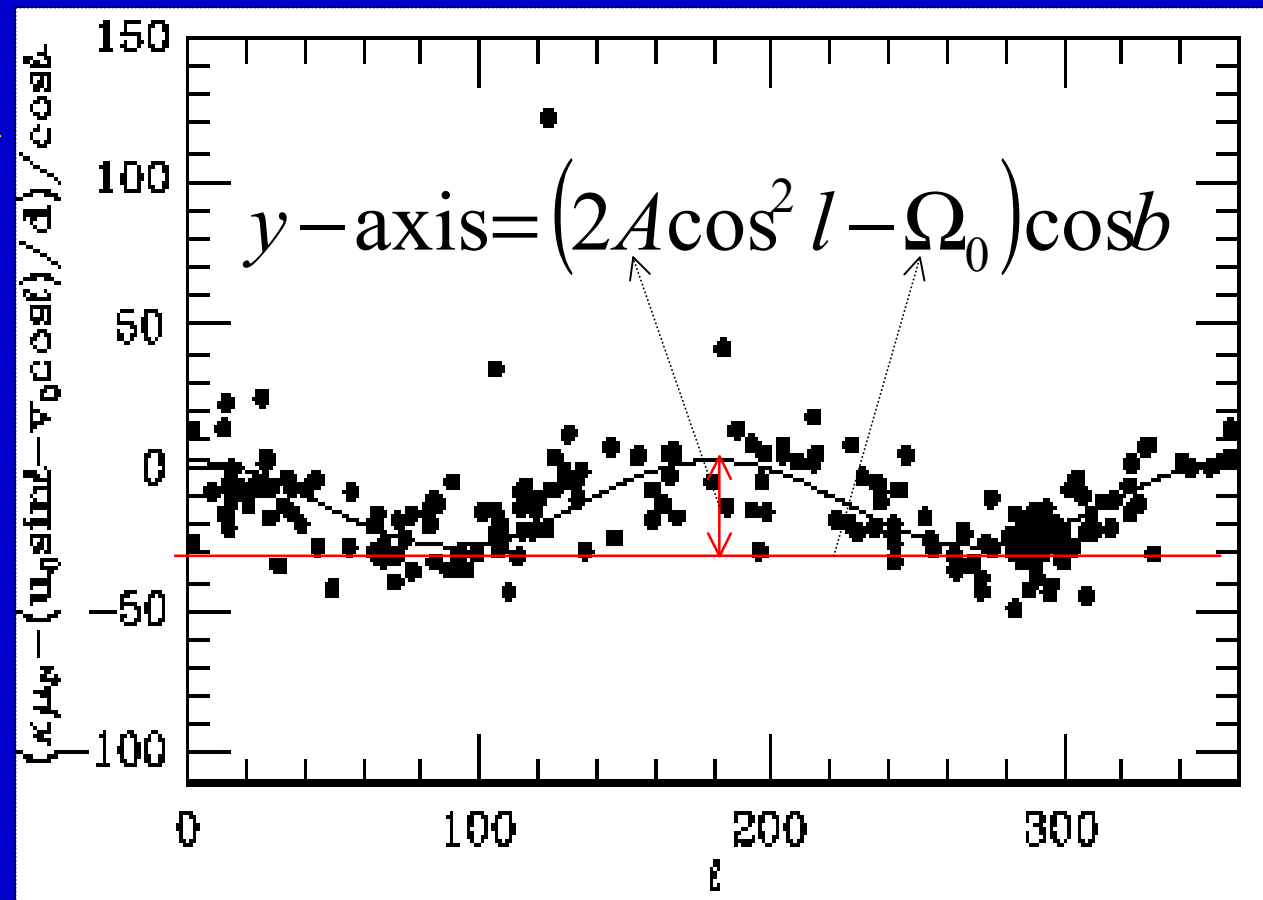
Understanding our viewpoint: the Oort Constants [1]

$$A = -\frac{1}{2} R_0 \left(\frac{d\Omega}{dR} \right)_0 \qquad B = -\Omega_0 + A$$
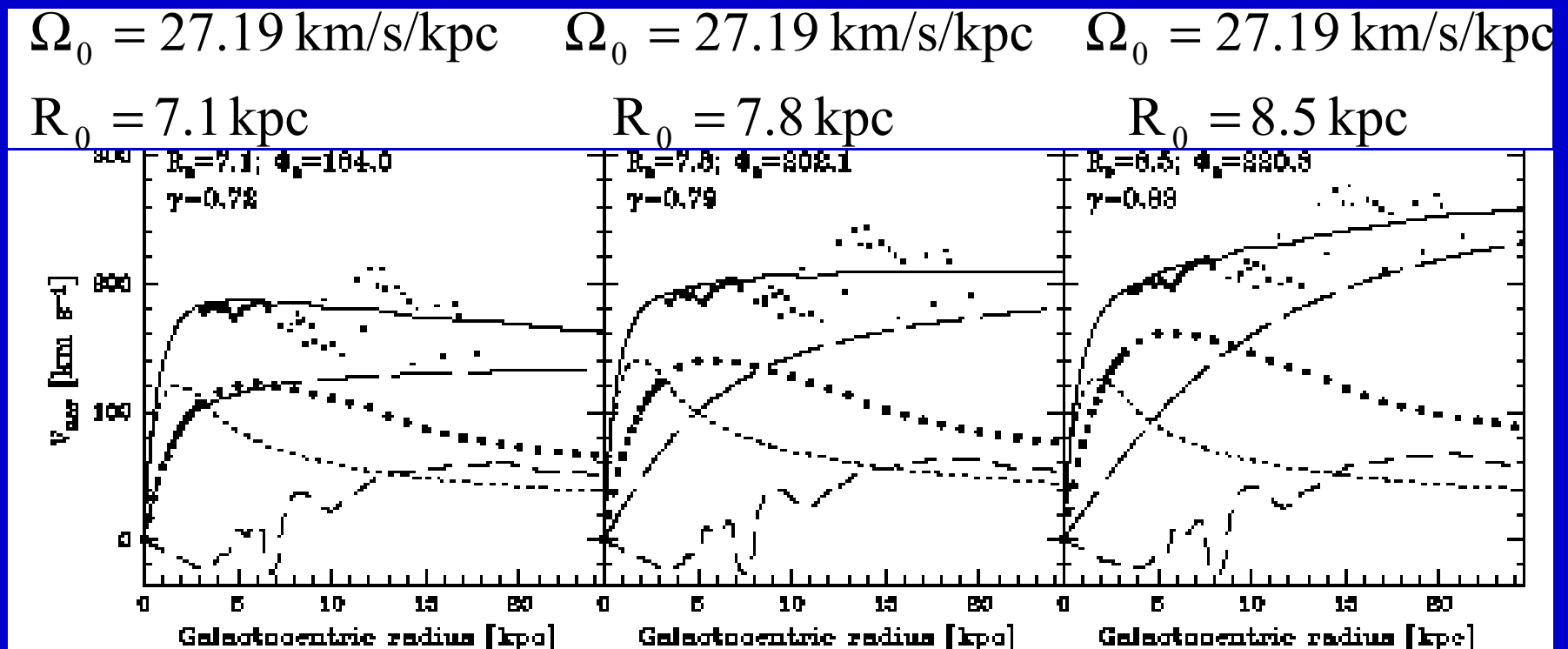
$$\Omega_0 = 27.19 \pm 0.87 \ \text{km/s/kpc}$$

E.g. Feast & Whitelock (1998), from HIPPARCOS proper motions of 220 cepheids. [3]

See Reid et al (1999) for measurement from SgrA* [4]

$$y-\text{axis} = \left(2A\cos^2 l - \Omega_0 \right)\cos b$$

Remaining problems: unknown distance to Galactic center and large errors beyond Solar Circle.

e.g. Olling & Merrifield (1999) [5] constructed three possible rotation curves using Feast & Whitelock's result and assuming........

$\Omega_0 = 27.19\,\mathrm{km/s/kpc}$ $\Omega_0 = 27.19\,\mathrm{km/s/kpc}$ $\Omega_0 = 27.19\,\mathrm{km/s/kpc}$

$R_0 = 7.1\,\mathrm{kpc}$ $R_0 = 7.8\,\mathrm{kpc}$ $R_0 = 8.5\,\mathrm{kpc}$

How would improvements in astrometry help?

Distance to Galactic center: few μas accuracies allow R_0 to 1% with 100 stars

=> the Oort Constants are history!

Rotation Curve: test by "observing" 250 Cepheids in a simulated rotating disk, with d < 20 kpc , < 5km/s proper motion and radial velocity accuracy (Johnston, Tremaine & Spergel, *in preparation*)……..
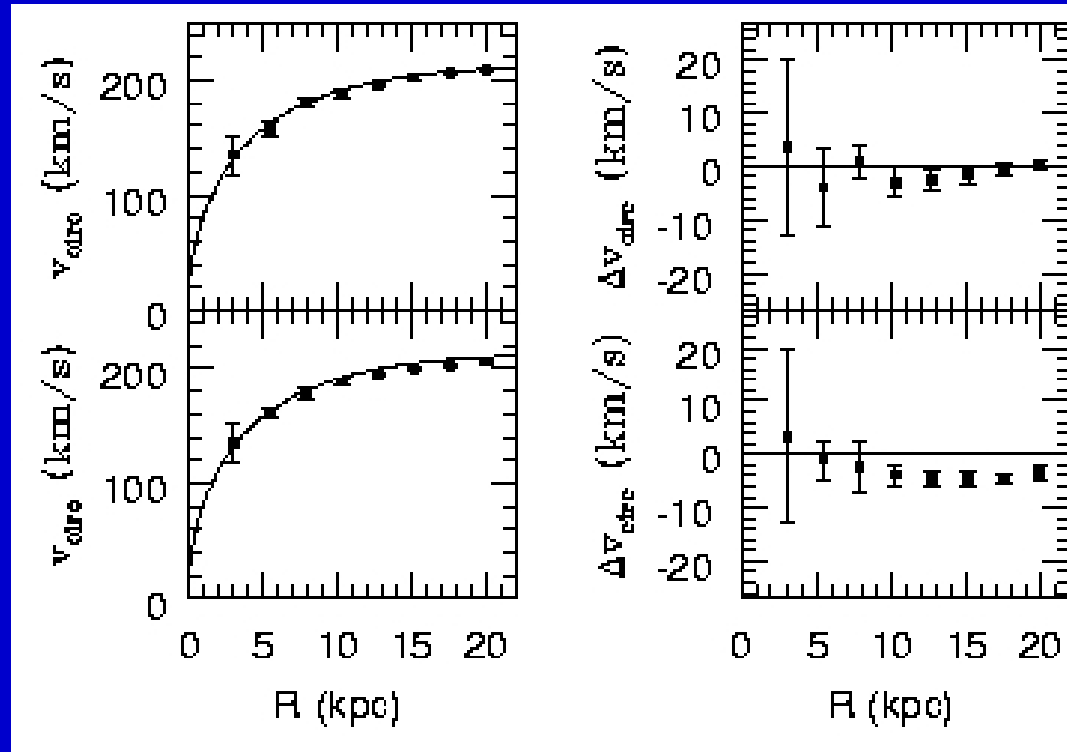
.....with perfect knowledge of our reference frame

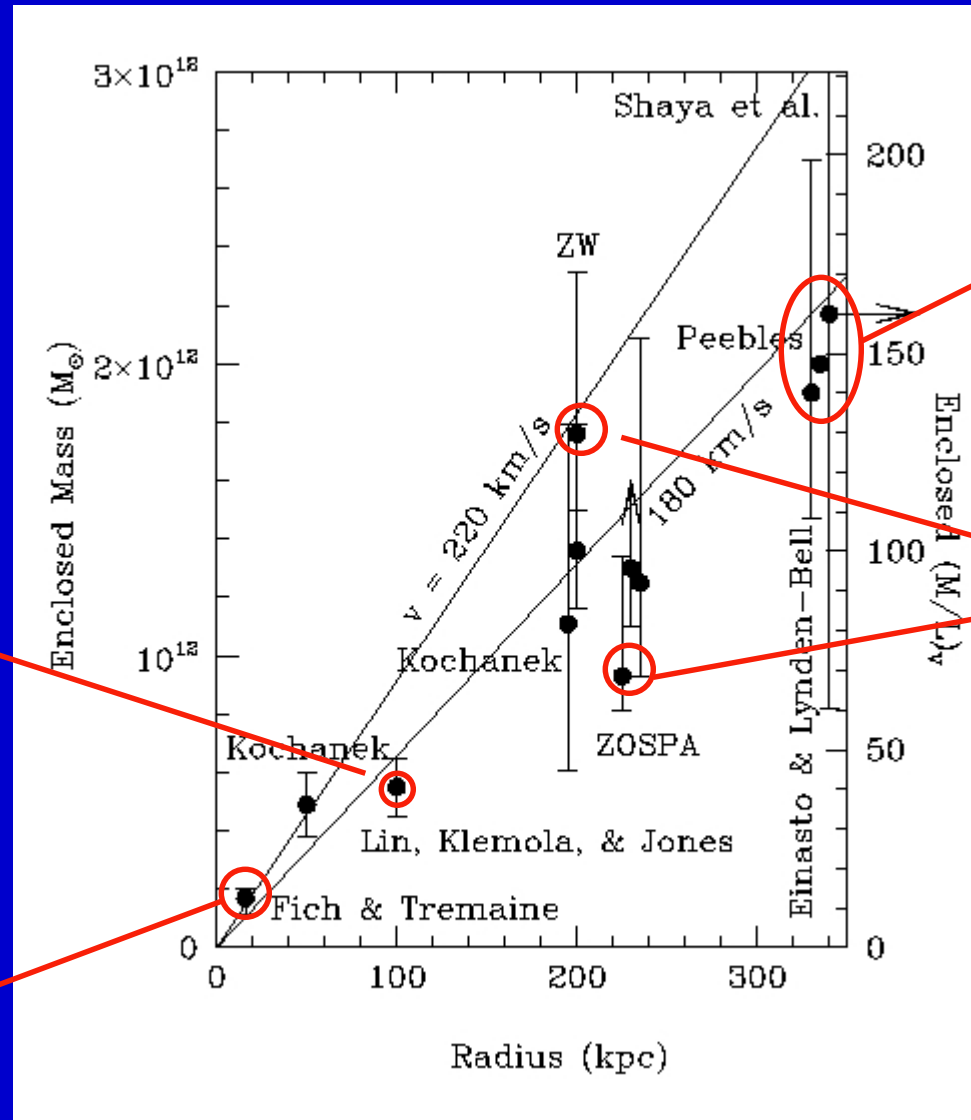.....with both distance and motion at Solar Circle underestimated by 1%

Note: important for measuring/understanding warp and spiral arms etc

2. Dark Matter Halo

Current state of dark matter halo measurments (Zaritsky, 1999) [6]

Tidal debris from Magellanic Clouds

Disk rotation curve

From the "timing argument"

From satellite motions

## Measuring the mass in the halo with a random population:

e.g. Wilkinson & Evans (1999) [10] used 27 Galactic satellites/globular clusters (>20 kpc away), 6 with proper motion measurements to find

$$5.4(+0.2-3.6)\times 10^{11}\,M_{\text{Solar}} \quad \text{within 50kpc}$$

10μas astrometry would decrease errors to 20% (and this would improve with a larger sample - e.g. random halo stars)

Problem: is the population really random?

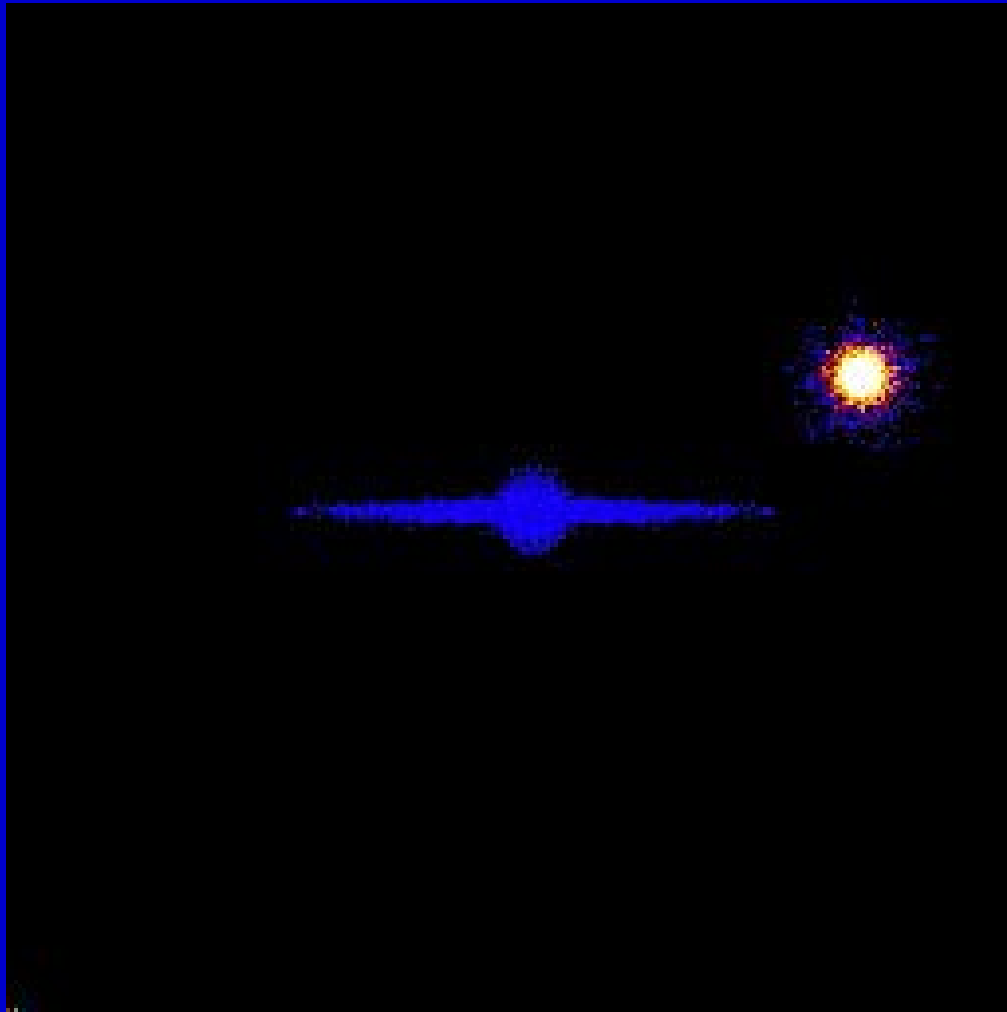Beyond 10-20kpc both theoretical ideas and observational evidence suggest the stellar distribution is very LUMPY.
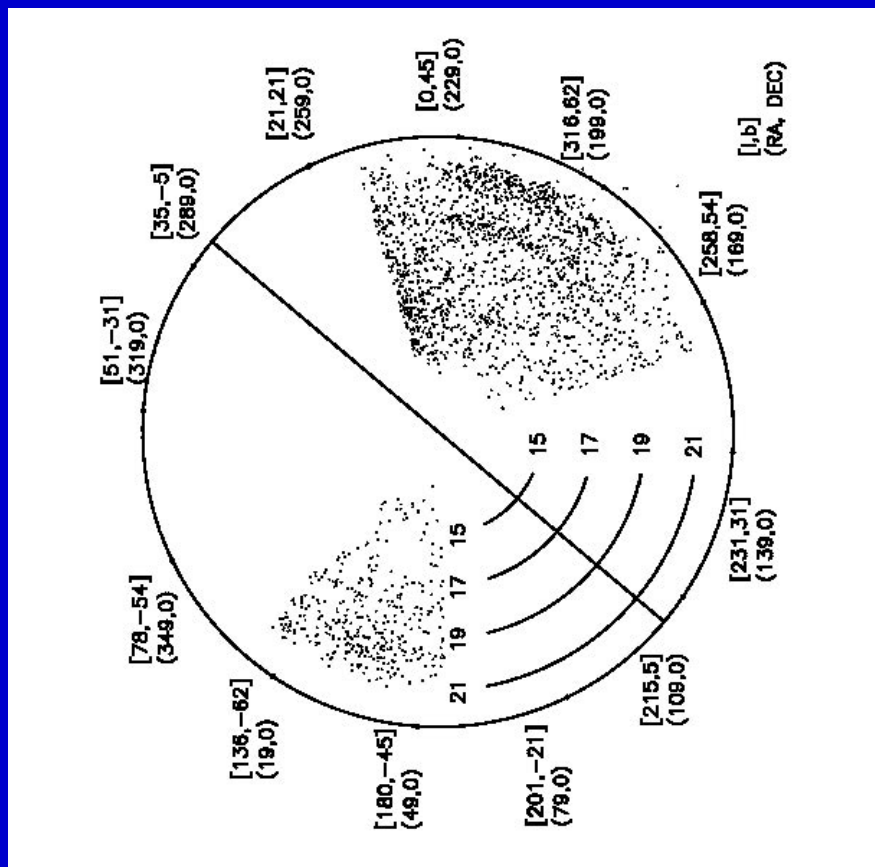
E.g. distribution of A-colored stars in SDSS g* magnitudes - slice 2.52 degrees deep (Yanny et al, 2000). [9]

Faintest star g*=21, or about 100 kpc away

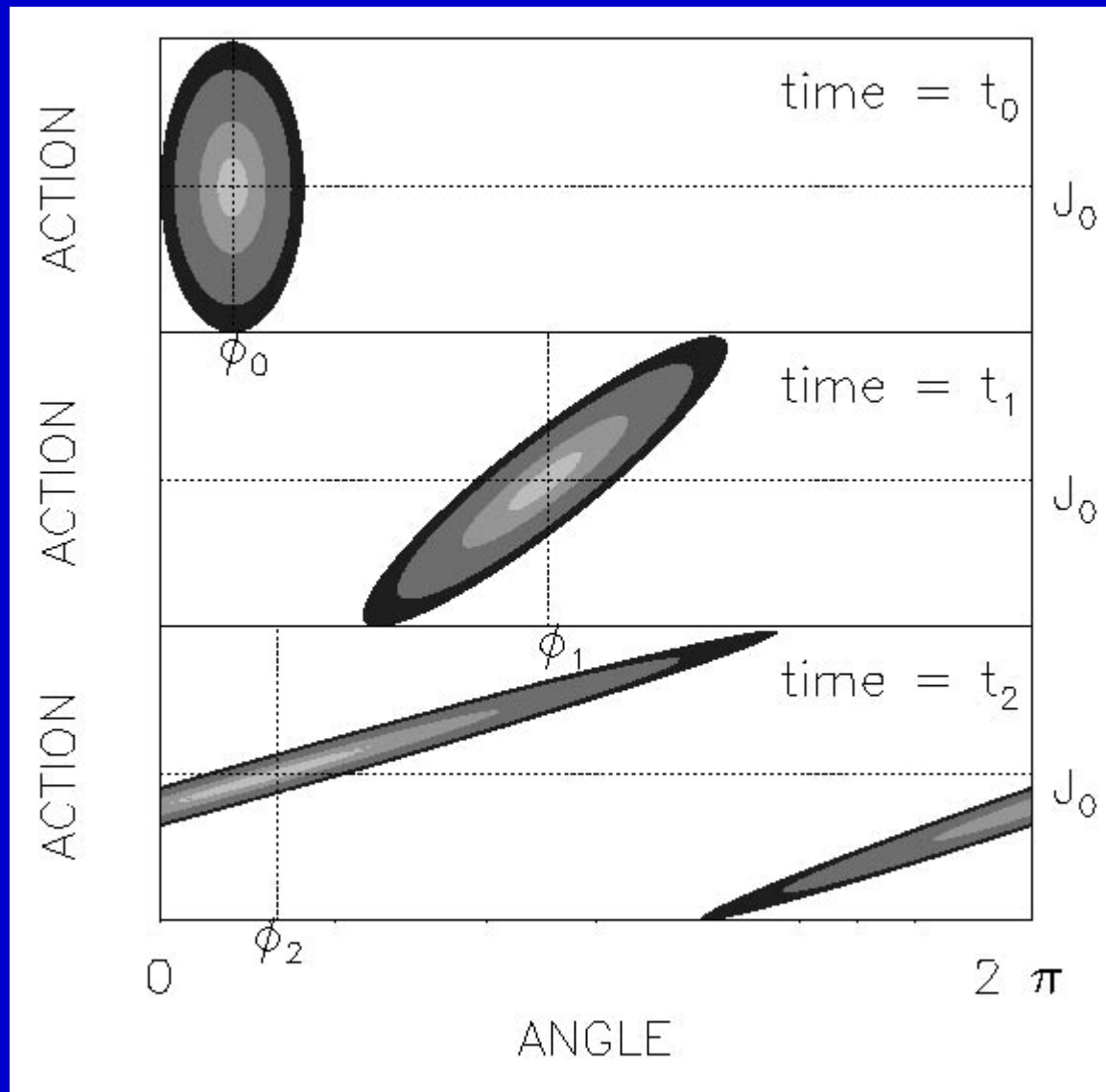(see also [7,8,11,12])

# Alternative: use tidal debris streams [13] from Galactic satellites as a probe [14-17]

Why?

• Strong evidence that they exist (I.e. they ARE the structure beyond 10 kpc, e.g. in SDSS)

• They're dynamically cold, and so make excellent tracers (just as disk stars do)

Once stars are unbound from a satellite they only feel the Milky Way's potential, and simply phase-mix along the orbit, conserving their orbital properties (e.g. energy).

Figure from Helmi & White (1999) [18] (also [19])

q=1.0
simulation
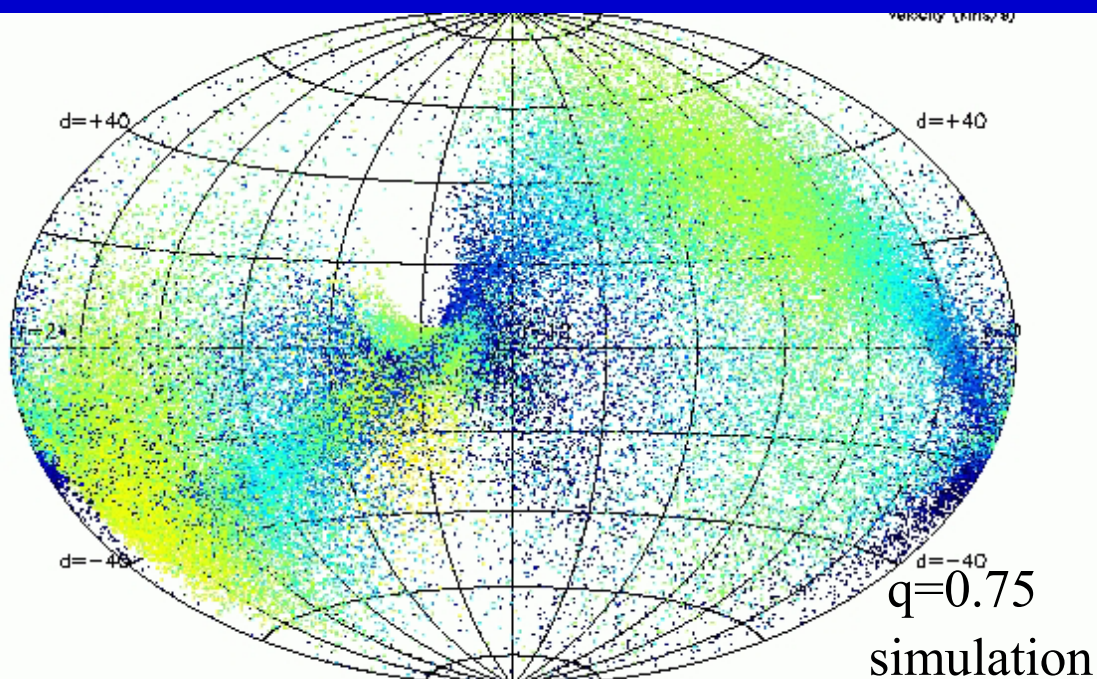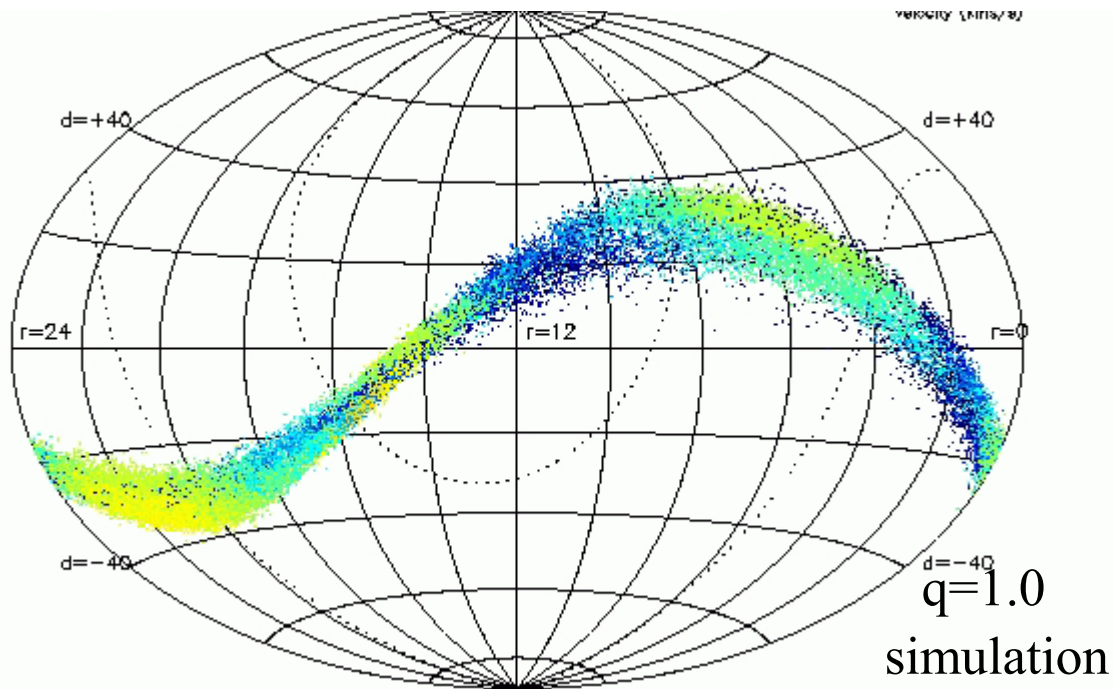
q=0.75
simulation

E.g. Ibata et al (2000) found 35 Carbon stars within 10 degrees of Sagittarius' orbital plane and used this to show that the dark matter halo must be close to spherical (q=1) rather than highly flattened (q=0.75) [12]

How would improvements in astrometry help?

Few micro-arcsecond astrometry allows us to measure proper motions with few km/s accuracies at 100kpc

One approach (Johnston, Zhao, Spergel & Hernquist, 1999) [14,15]
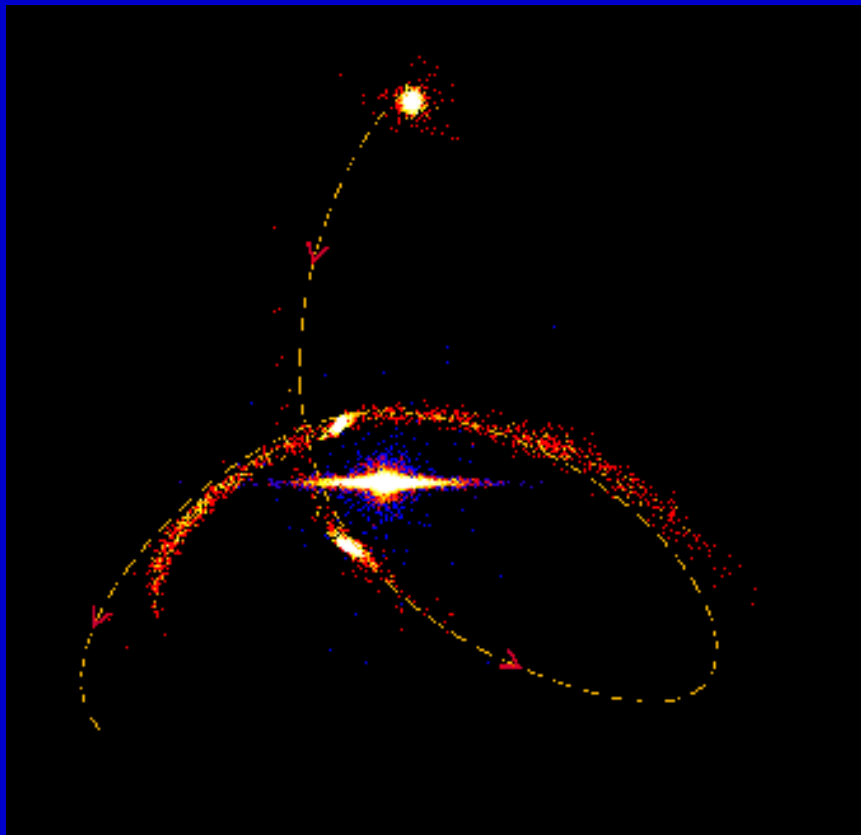
Algorithm:

• Measure full phase-space coordinates of satellite

• Measure angular positions, radial velocities and proper motions of stars in debris stream

• Assume a form for the Galactic potential

• Estimate distances to stars using energy conservation

• Integrate stars and satellite backwards

The "best" potential is the one in which most stars recombine with the satellite.
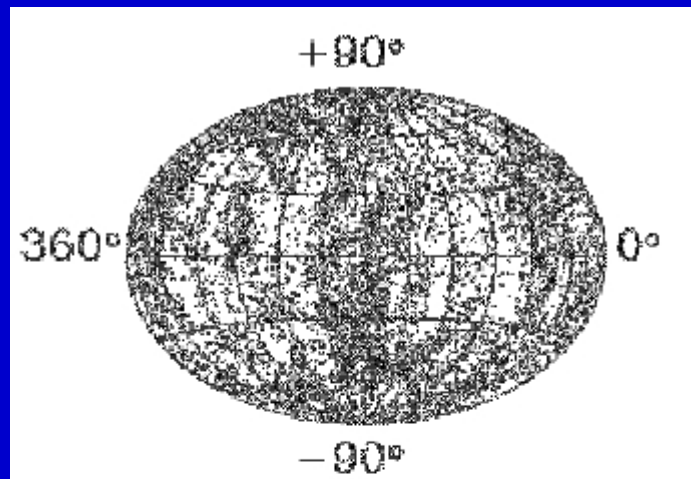
This method recovers the shape, mass and extent of the dark matter halo with few % accuracies using just 100 stars
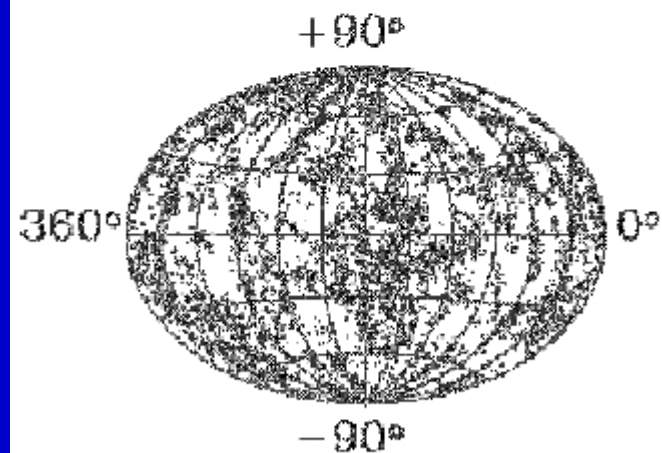
3. Galaxy Formation
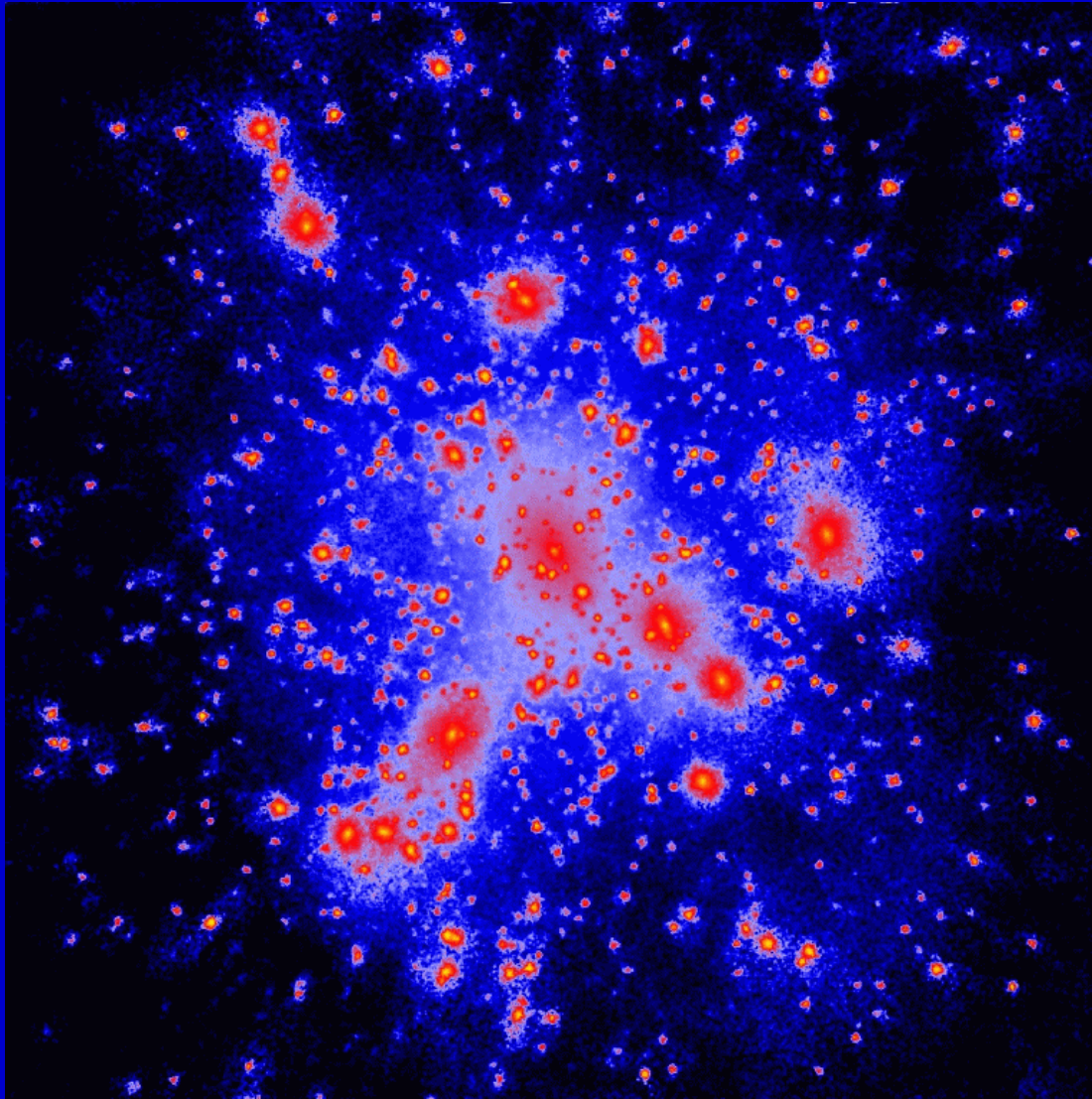
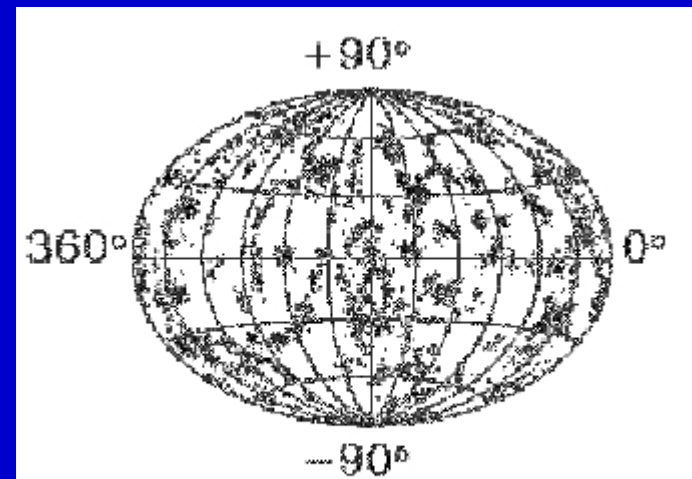Currently favoured picture of galaxy formation: "hierarchical clustering".

E.g. end point of N-body simulation of a single galactic halo from Moore et al (1999) [20] (also [21])

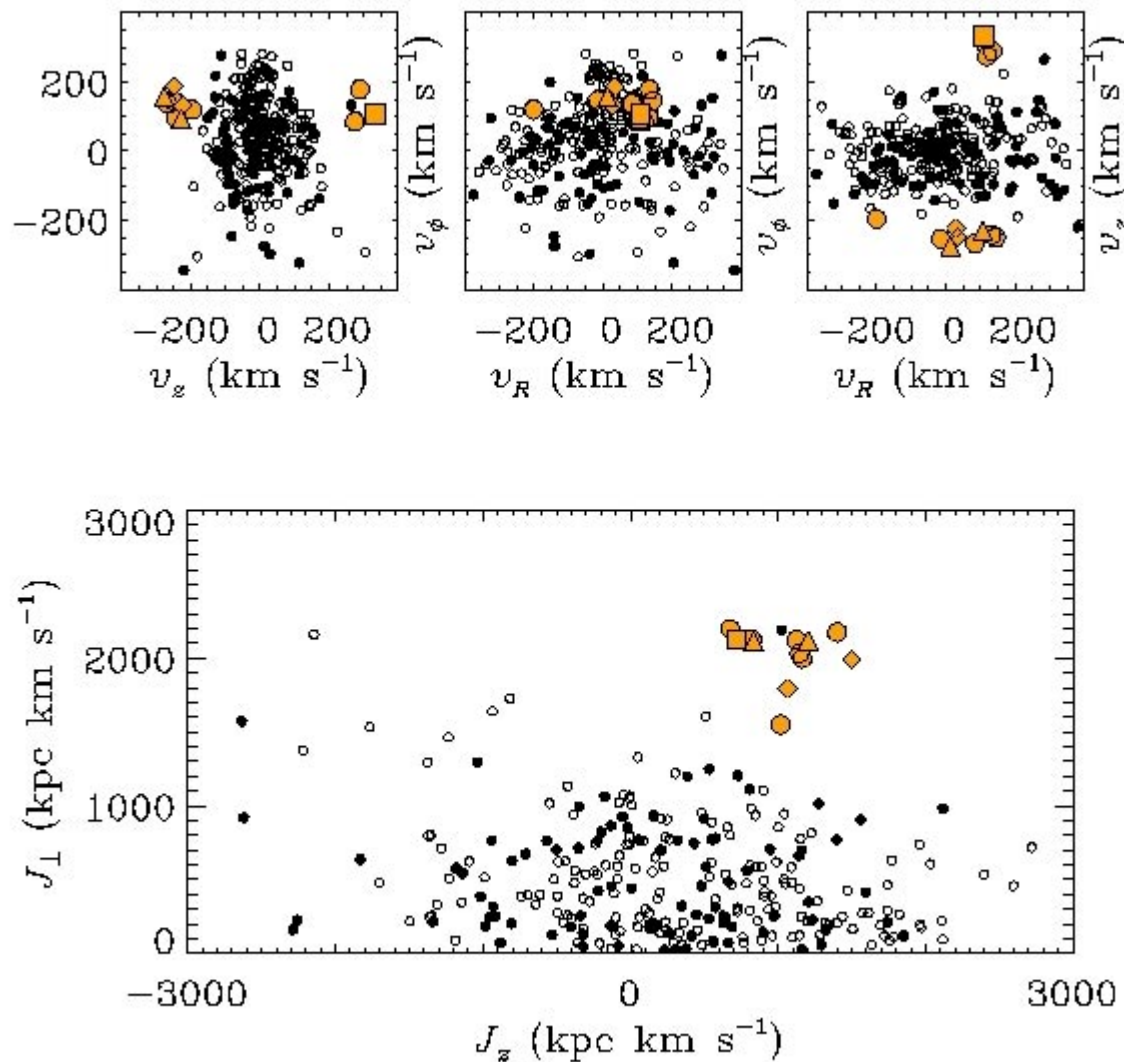20 kpc < R < 30 kpc

40 kpc < R < 50 kpc

60 kpc < R < 70 kpc

Put this together with debris streams and you get SDSS-like structures (Bullock et al, 2000) [22]

We also see evidence for streams in the Solar Neighbourhood

e.g. 95 giant stars within 1 kpc of Sun exhibit an odd moving group, possibly the relic of a satellite (Helmi et al 1999 [8])
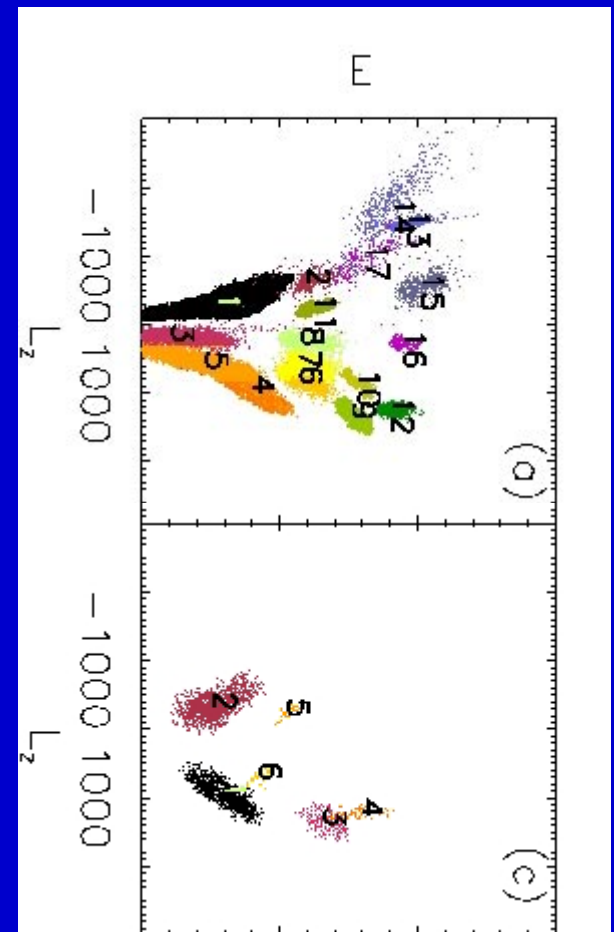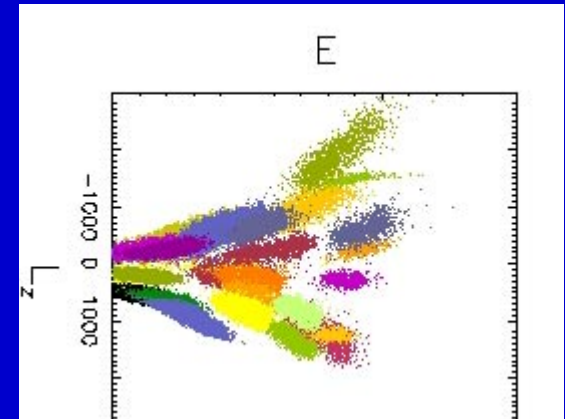
How will improvements in astrometry help?

E.g. Helmi & de Zeeuw (2000) [23]

Orbital properties of simulated debris

Recovery with GAIA (I.e. 10 micro-arcsecond)

Recovery with FAME (I.e. 50-200 micro-arcsecond)

4. Summary

Improvements in astrometric accuracy in the next decade will revolutionize our knowledge of:

- **our reference frame**

- **the Galactic rotation curve**

- **our dark matter halo**

- **galaxy formation models**

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